AD 253 431

Technical Report 123

METHODS OF SHOTCRETE CONSTRUCTION FOR PERSONNEL SHELTERS

17 March 1961

U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

METHODS OF SHOTCRETE CONSTRUCTION FOR PERSONNEL SHELTERS

Y-F011-05-328

Type C

by

R. M. Webb

OBJECT OF TASK

To develop an economical arch-shaped concrete structure to serve as an alternate to existing standard shelters now included in NAVDOCKS TP-PL-8.

ABSTRACT

To evaluate methods for the economical construction of shotcrete personnel shelters, shotcrete arches were cast over various forms: a Quonset arch, a flexible plywood shell, a pneumatic airform, and a compacted earth mound. Salvageable Quonsets were found to be the most economical. Wet-mix shotcrete containing coarse aggregate was placed which permitted use of conventional concrete mixes.

CONTENTS

CONTENTS (Cont'd)

INTRODUCTION

Reinforced concrete arches tested at the Nevada Test Site provided sufficient strength to resist high overpressures without incurring serious damage.[1] These arches offered advantages over metal arches by providing greater radiation protection, by being easier to waterproof, and by being constructed of materials which are noncritical in time of war. The disadvantages of these arches in comparison with metal arches are higher initial cost and less structural flexibility. It is believed the former disadvantage has been partly overcome by development of new methods for construction of concrete arches.

The purpose of the present task, as defined by BUDOCKS, was to develop an economical concrete structure to serve as an alternate to existing standard shelters. The plans to accomplish this purpose were: (1) to investigate shotcrete (pneumatically placed concrete) as a method for construction of shelters; and (2) to develop a full-scale prototype. The material presented in this report is intended to meet objective (1).

Preliminary experiments indicated that concrete containing coarse aggregate could be applied pneumatically, and that economical methods of forming arches could readily be devised. In the following sections placement of shotcrete and various forming methods are discussed, and relative man-hour requirements and relative form costs for shotcrete shelter construction are presented.

SHOTCRETE

There are basically two types of shotcrete: dry mix and wet mix. In a dry mix, sand and cement are combined in a mixer and the mixing water is added at the discharge nozzle of the material hose. In a wet mix, water and the dry materials are integrated in the mixer. The latter was used in the Laboratory's experiments. Wet-mix shotcrete has the advantage over dry-mix shotcrete of controlled water-cement ratio and of concomitant reduction in rebound. Wet-mix shotcrete designs are discussed in Appendix A. Dry-mix design methods are given in the literature.[2]

MIXING AND PLACEMENT

A general view of a mixing and placing operation is shown in Figure 1. Detailed considerations of shotcrete design, placement and forming methods are given in Appendixes A and B. Crew requirements are given in Appendix C. A schematic diagram of a wet-mix shotcrete machine and a list of accessory equipment are given in Appendix D.

Batching

Originally the fine and coarse aggregates were weighed on a stationary scale, transported to the mixing machine by a fork-lift truck in a forward tilt-dump hopper (Figure 1) and then hand-shoveled into the mixer. Hand-shoveling proved to be too slow, hence an improvised mechanical material loader (Figure 2) was used.

Figure 1. Mixing and placing operation.

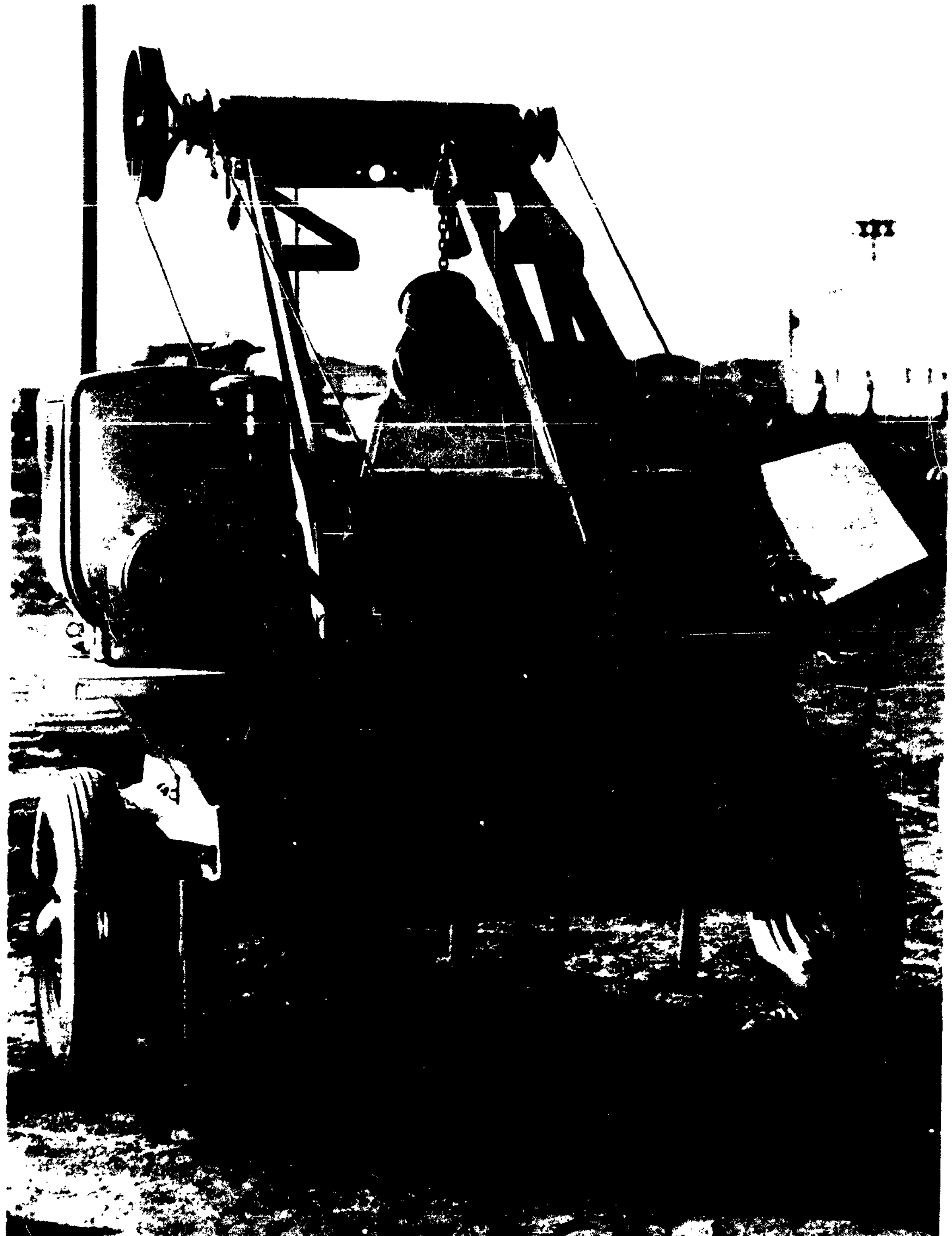


Figure 2. Modified shotcrete loader.

The procedure for mixing shotcrete was as follows: (1) The forward tilt-dump hopper (Figure 1) was placed on batch scales, then the fine aggregate was hand-shoveled into the hopper and weighed. Coarse aggregates were then shoveled into the hopper until the total weight of fine plus coarse aggregate was obtained. (2) The materials were transported to the material loader (Figures 1 and 2) and put in the loader hopper (Figure 2). (3) Cement was placed in the loader, then all dry materials were put in the shotcrete material chamber (approximately 10 percent of the total mixing water had been previously added to the mixing chamber). (4) The required amount of mixing water was added.

It was observed that very rich mixes became lumpy. When this condition occurred, it was corrected by adding all of the mixing water after the dry materials had been placed in the material chamber. The cycling time per mixing chamber (two chambers having alternate operating cycles) was approximately one minute; therefore, the material loading had to be accomplished quickly and efficiently.

Placement

Approximately 100 cubic yards of wet-mix shotcrete were placed in the construction of 20-foot-diameter semicircular arches during the Laboratory's experiments. In addition, the placement by contractors of more than 500 cubic yards of shotcrete on various types of forms was observed. The method of shotcreting varied with the type of equipment and scaffolding used. The same basic techniques, however, were used on the various jobs observed.

The shotcrete work at the Laboratory proceeded essentially as follows: (1) the form surfaces were cleaned of foreign materials; (2) a light oil film was sprayed on the form to provide a bond break; (3) conventional reinforcing steel was placed circumferentially in both the inner and outer faces of the arch and a layer of 6 x 6-2/2 welded wire mesh was placed in both faces to prevent the shotcrete from sliding on the curved form; and (4) the arch was cast.

In placing the shotcrete, the nozzle was held about 3 feet from the form, at right angles to the surface. To insure a smooth intrados, objectionable rebound was cleared from the form with a high-pressure air jet. The arch was cast in two layers. The first covered the inner reinforcement over the entire formed surface; the second consisted of the remaining arch thickness. Both layers were cast by balancing the height of lift on each side of the center line of the form. The maximum unbalanced lift did not exceed 5 feet. When the second layer could not be cast in one continuous operation, joints were made by sloping the shotcrete at 45 degrees to a thin, clean, regular edge. Before placing new material, the face of the joint and the adjacent shotcrete was

thoroughly wetted and scoured with an air jet. Upon completion of the work, the concrete surface of the arch was cured by application of two coats of an approved concrete curing compound.

Certain exceptions to these general procedures are described in the discussion of forms and further particulars are given in Appendix A.

Rebound

Rebound is material that bounces from surfaces where shotcrete is applied. The amount of rebound was measured by catching the waste on a tarpaulin and weighing it. Rebound from a hard surface approximated 50 percent, diminishing as fresh concrete was applied. The average rebound during the placement of 25 cubic yards of shotcrete was 15 percent.

FORMS

In the event of an emergency construction program for shelters it would be necessary to use readily available materials. This consideration governed to a large extent the choice of forming methods studied. Those considered included the salvageable Quonset, stressed-skin plywood shells, compacted-earth mounds, and the pneumatic form.

Quonset Form

A metal Quonset with a 20-foot span was cut into 8-foot and 12-foot sections to facilitate removal of the form within the limits of excavation for a buried shelter. The sections were placed on concrete footings and braced by metal floor stringers to prevent lateral movement at the base of the form. Foundation details are given in Appendix B.

An 8-inch-thick shotcrete arch similar to the concrete arches tested at the Nevada Test Site[1] was cast over the Quonset form (Figures 1 and 3). This produced a maximum downward deflection of 0.17 inch at the crown. After the shotcrete had set for 72 hours the form was removed, as described in Appendix B, and the intrados was inspected for blemishes. Minor surface blemishes were observed, attributable to faulty mix design and inadequate clearing of rebound from the form surface.

Flexible Plywood Forms

Flexible plywood forms were used in casting 12-inch-thick shotcrete arches. This is the maximum thickness required by current methods of design for a 100-psi buried shelter with a 20-foot span.[3,4,5] Two forming techniques, Method A and Method B, were developed. Structural details are given in Appendix B.

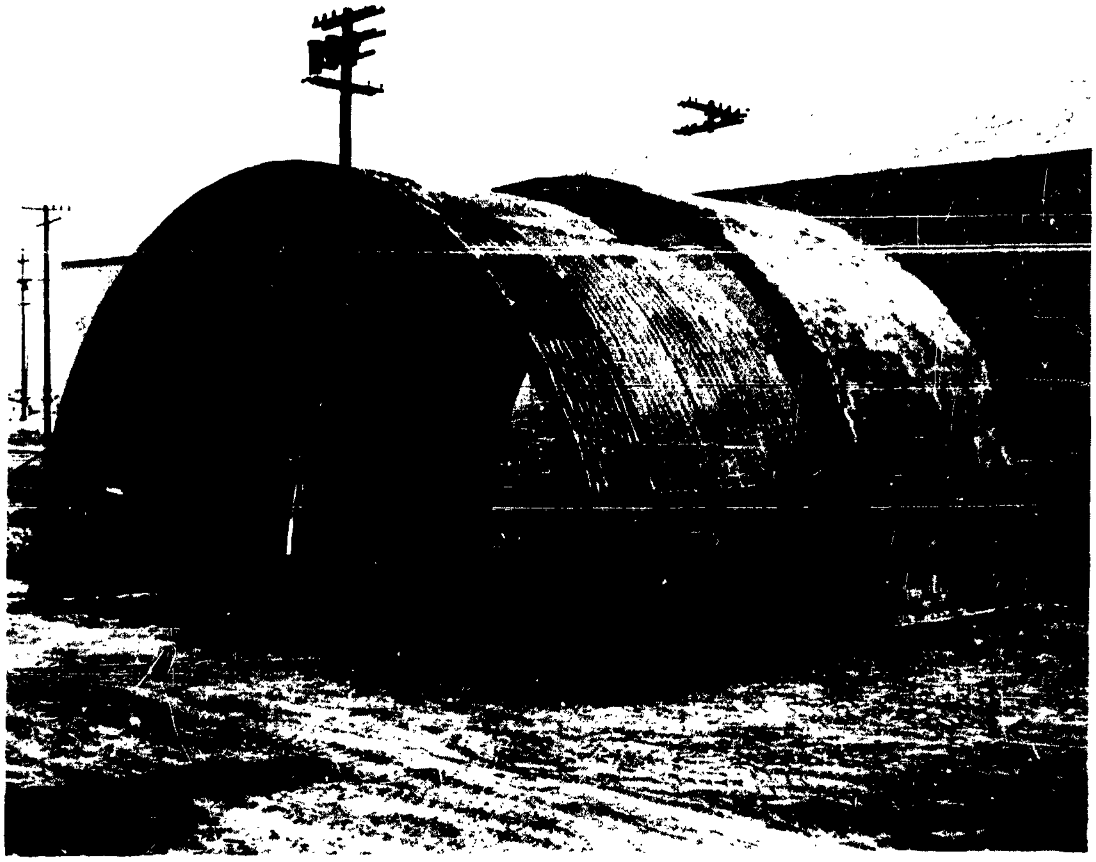


Figure 3. Quonset form and shotcrete arch.

Method A Form. Method A (Figure 14, Appendix B) used 4-foot by 8-foot plywood panels bent by prestressing cables. The panels were interlocked by bolting together 2-inch by 4-inch wooden form wales. To provide rigidity against vertical deflections of the crown, form ties with conventional pigtails were inserted between the wales at the apex joint and the pigtails were welded to the circumferential reinforcing steel. Details of the erection procedure are given in Appendix B.

The Method A form was surprisingly rigid; only a 3/16-inch downward deflection at the apex resulted from the shotcrete placement. The 3/16-inch deflection was the maximum radial deflection observed. The arch was cured for 72 hours; then each form panel was removed manually after stressing the panel chord cables, loosening all long chord cables, and removing all the tie bolts from the form wales.

Method B Form. Method B (Figure 15, Appendix B) consisted of a prefabricated reinforcing steel cage supporting a 3/8-inch plywood lining by means of form ties and wales. The plywood lining was similar to that of Method A except that form ties were used in place of prestressing cables. The prefabricated cage incorporated circumferential trussed bars to which form-tie pigtails were welded. The trussed bars had webs of 3/8-inch-diameter reinforcing steel.

In loading the form the shotcrete was started on one side at the bottom and built upward in one continuous lift from springing to crown. Though the unbalanced lift imposed a severe load on the form, only a 3/16-inch maximum radial deflection resulted. After casting, the shotcrete was cured for 72 hours before the individual form panels were removed.

Earth Mound Form

The method for determining the feasibility of earth mound forming was to construct a shotcrete shelter over a compacted-earth form (earth mound constructed initially by use of partial plywood forming), then to evaluate methods of excavating the fill from the shotcrete arch with available construction equipment. The economy of this method depends on the properties of the available earth fill materials, the topography of the construction site, the kind of construction equipment available, and the experience of the constructors.

Fill Materials. The mound was constructed of a black sandy clay with the following properties:

Maximum dry density - 114.1 lb per cu ft

Optimum moisture - 13.1 percent

Mechanical analysis - 99.7 percent passing the No. 60 sieve, 63 percent passing the No. 140 sieve, and 43.5 percent passing the No. 200 sieve

The material was stockpiled at the construction site, graded into windrows, sprinkled with water from a garden hose (to obtain optimum compaction density), and conditioned for compaction with a mechanical pulvimixer.

Construction. The earth fill was hauled from the material pile and spread in 6-inch-thick vertical layers with the blade of a front-end loader, then compacted with a triple-headed pneumatic tamper. By this method, illustrated in Figures 4, 5 and 6, the mound was built at an average rate of 7 cubic yards of fill per hour.

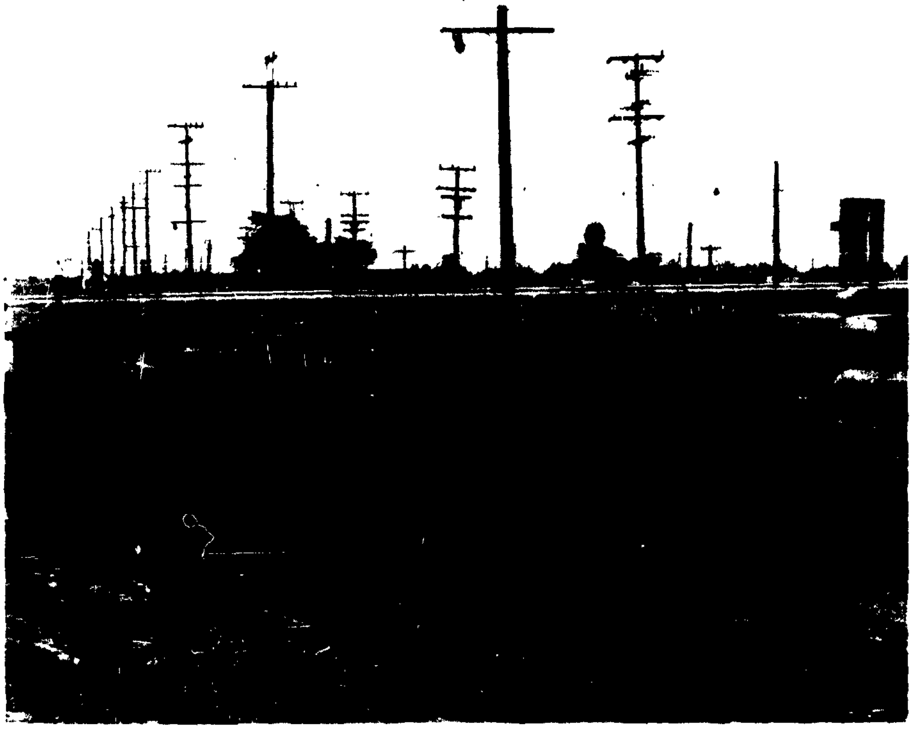


Figure 4. Preparation of fill for earth mound form.

Figure 5. Construction of earth mound form.

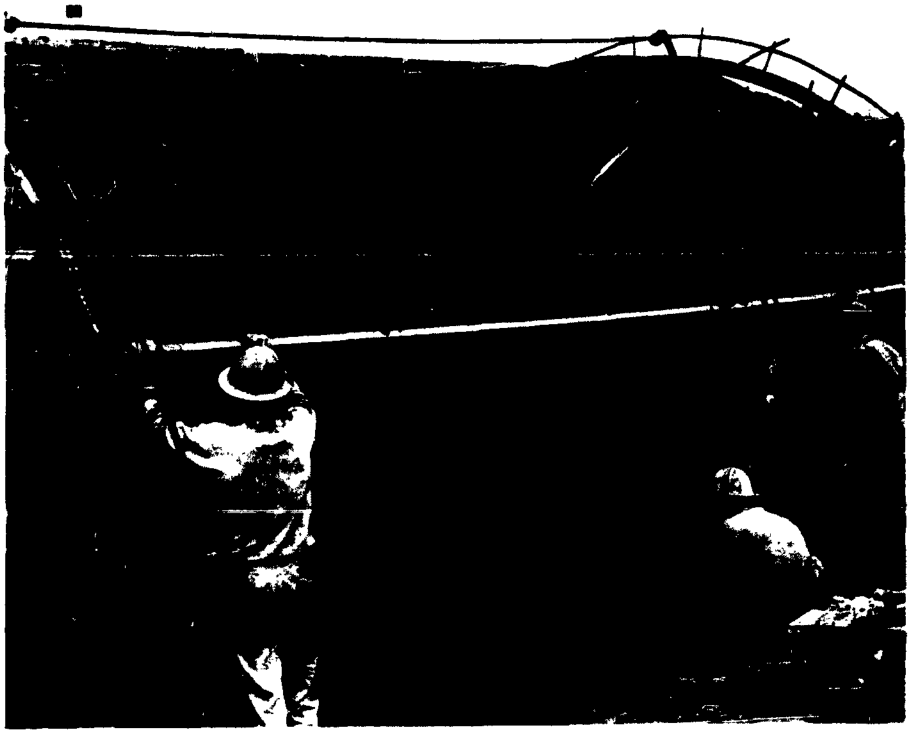


Figure 6. Earth mound form surface — screeded finish.

During the evening between the first and second day of construction an unusually high tide inundated the earth mound site, causing a horizontal spread of the earth mound and the plywood forms. The repair of the damage utilized an unusual but successful application of the pneumatic gun equipment. The mound was cut back, then a mixture of three parts of sand to one part of earth was shot on the surface until the original dimensions were obtained. The earth was placed at a sufficiently low moisture content so that no sloughing occurred. This method of soil placement was so successful that it was used to bring the mound surface to a true semicircle. To accomplish this, two interlaced Quonset ribs were placed to assist in screeding; a mixture of cement, soil and sand in the ratio of 1:4:10 was shot on the mound surface; then the surface was screeded to a semicircle (Figure 6). Construction of the 25-foot-long mound, including excavation, haul time, and conditioning of backfill materials, required 370 man-hours.

A recommended formwork for earth mound construction is given in Figure 16 of Appendix B.

Surface Treatment. To protect the earth form from the effects of the air jet used for removing rebound and to determine the effects various cover materials would have on the interior finish of the shotcrete arch, the following materials were investigated:

1. Lightweight plastic tarpaulin, covering a 5-foot longitudinal section of the mound.

2. Roofing felt, covering a 5-foot section.

3. Wire-reinforced plaster paper, covering a 5-foot section.

4. Soil-cement stabilization, covering a 10-foot section.

The lap edges of the covering materials were stapled to the mound with 3-inch-long 16-gage wire hairpins. The resulting interior shotcrete finishes are shown in Figure 7.

The lightweight plastic tarpaulin furnished an exceptionally smooth interior finish. At first the shotcrete was hard to place over the plastic. It would not adhere when placed in thicknesses greater than 1/4 inch. To correct this, a 1/4-inch shotcrete coat was placed over the tarp and allowed to take an initial set, then the remaining arch thickness was placed in the usual manner.

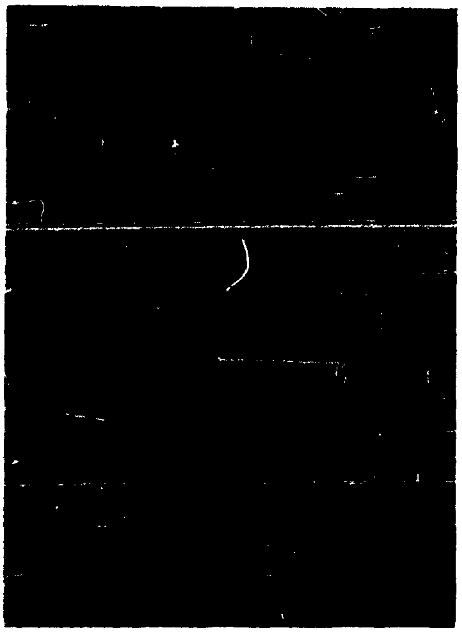
The roofing felt stuck to the concrete and was hard to remove. Possibly, a form oil film on the felt surface would correct this condition. The wire reinforcing in the plaster paper also clung to the concrete. This indicated that the paper should have been wax-glazed or film-oiled; shotcrete will cling to a film-oiled surface, but it will not stick so fast that it cannot be removed.

The soil-cement surface was not disturbed by the air jet and a fairly clean interior finish was furnished. However, the soil-cement stuck to the arch and had to be water-soaked and then scraped off.

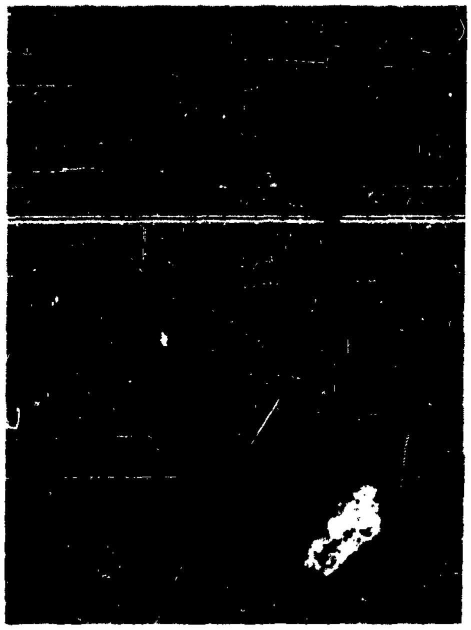
Excavation. Two types of Navy equipment were used to excavate the earth from within the concrete arch:

1. A front-end loader of the type which elevates the front-end loading mechanism by hydraulic cylinder actuation of the loader carriage. The front-end loader excavated the mound at an average rate of 14.5 cubic yards per hour.

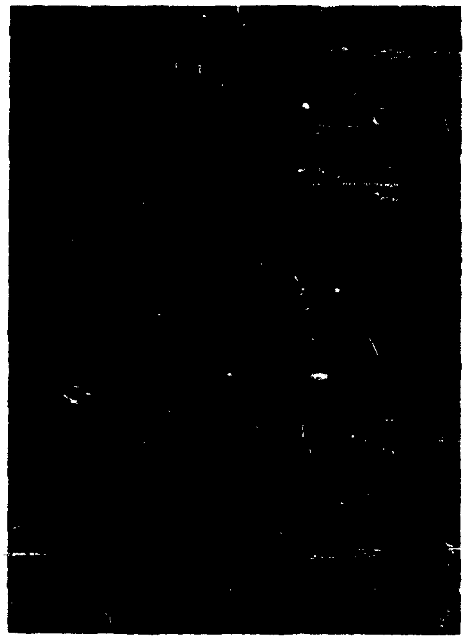
2. A small track-mounted trenching machine consisting of a ladder-bucket type excavator capable of digging throughout a 30-degree arc (measured from the normal operating position of the ladder).



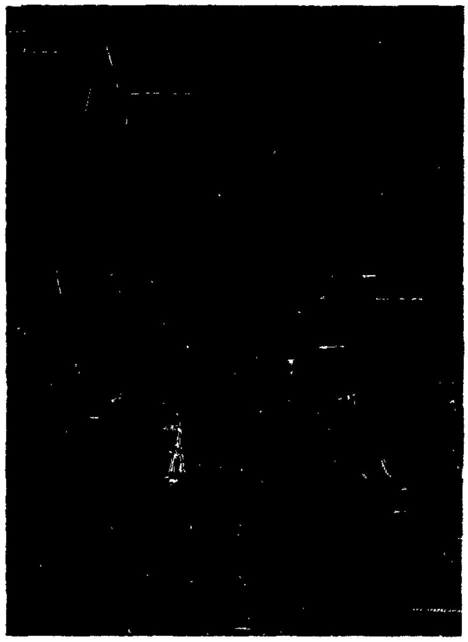
A - Plastic tarp finish



B - Roofing felt-paper finish



C - Building paper finish



D - Soil-cement finish

Figure 7. Interior finishes of earth mound shell.

The trenching machine had to be used in an unorthodox manner. It was operated in reverse and backed into the material to be excavated. As this particular machine did not have a reversing mechanism to allow reversal in rotation of the ladder chain drive, it was used as a scraper rather than as a digger. Such operation greatly reduced the excavating capabilities of the machine. In this mode of operation the trencher excavated 11 cubic yards per hour. A front-end loader was used to remove the material excavated by the trencher.

Desirable requirements for fill materials to increase the rate of excavation are discussed in Appendix B.

Pneumatic Form

A pneumatic form which is adaptable to shelter construction was formerly evaluated by the Laboratory and reported by Technical Note 167, 28 August 1953.[6] Information which is applicable for comparison with other methods presented in this report was abstracted from that report.

The pneumatic form is essentially a pressurized rubber balloon on which shotcrete is cast (Figure 8). By this method a dry-mix shotcrete[2] shell with overall dimensions of 26 feet 9 inches wide by 44 feet long by 12 feet 1-1/2 inches high was built which had a clear floor space of approximately 800 square feet.

The conclusions presented in TN-167 state that the pneumatic form proved successful for application of pneumatic mortar but that dimensional stability of the form was difficult to control.

Naval Magazine Structures

Eighteen ammunition magazines were constructed on contract at the U. S. Naval Ammunition Depot, Concord, California. The structures were pneumatically placed mortar arches 25 feet in span and 80 feet long. The concrete shell thickness varied from 6 to 11-1/4 inches from crown to springing. The circumferential reinforcing steel was No. 5 bars at 8-inch centers overlaid with 4 x 4-4/4 welded wire mesh. These structures were placed over sets of forms consisting of three hinged arches supported on screw jacks at the crown (Figure 9). During construction of the magazines, each set of forms received six re-uses. Analysis of the contract bids showed that a saving of 40 percent in form costs resulted from the use of shotcrete instead of conventionally placed concrete.

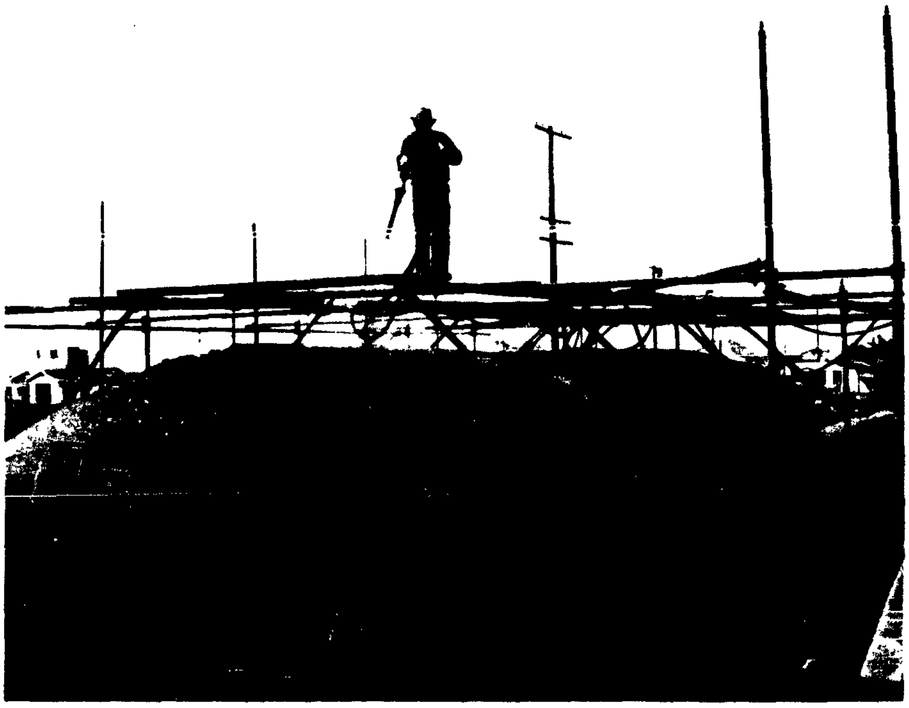


Figure 8. Pneumatic form construction.

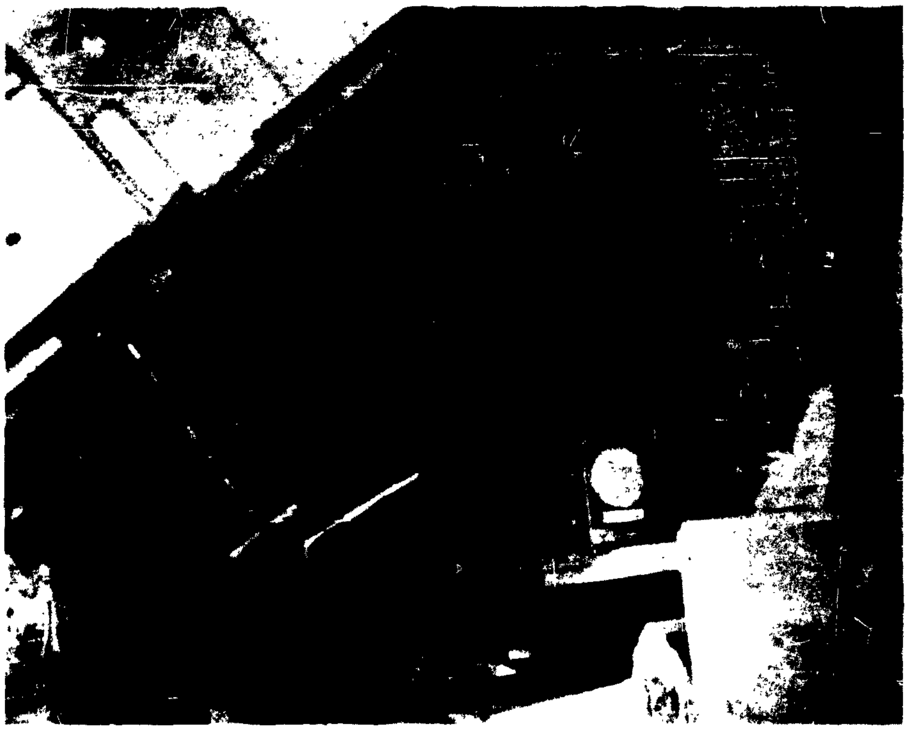


Figure 9. Form for ammunition magazine.

Relative Form Costs

Estimated relative form costs for the construction of a nominal 20-foot by 60-foot shelter are delineated in Figure 10. The estimates include: (1) the initial cost of form materials, (2) fabrication, erection and removal of the form, and (3) form maintenance charges. It is assumed that the labor will be performed by station forces.

The first part of the graph is based on the construction of a single shelter which provides 1200 square feet of floor space. The second part is based on the construction of three shelters — the maximum anticipated number of re-uses of the flexible plywood forms. The third part is based on the construction of six shelters — the maximum practical number of re-uses of the screw-jack forms. It was assumed that the salvageable Quonset forms could be obtained for $750.00. The salvage value of the form materials was not considered. The relative cost data for the pneumatic form may not be too realistic in that: (1) maintenance charges were based on a single use of the form; (2) the initial cost of a pneumatic form to cover 1200 square feet of floor area was estimated by proportion from the cost of an 800-square-foot form; and (3) rental forms possibly may be obtained.

To supplement the information of Figure 10, the estimated relative man-hour requirements for the construction of a single shelter are presented in Figure 11. Relative cost data which formed the basis for the information of Figures 10 and 11 is given in Table 1.

Job No. 3 (Table I) was bid for construction by conventional concrete placement methods and alternately for construction by shotcrete methods. The contract was awarded for shotcrete construction. Analysis of the bid showed that shotcrete construction resulted in a saving of 40 percent in form costs. Three sets of forms were required with each set receiving six re-uses. Discussions with numerous contractors revealed that shotcrete placement is bid the same as conventional concrete ($25 to $35 per cubic yard for labor plus materials). Direct costs (costs for labor and material) for the shotcrete placement work of job No. 3 was stated by the contractor to be $23 per cubic yard. The average placement rate was 53 cubic yards per 8-man crew per 8-hour day. Wages for the workmen were based on the then prevailing (1958) Department of Labor Wage Rates. This cost figure of $23 was reasonably verified, by prorating wage rates and production rates, in the Laboratory's shotcrete work.

Table I. Relative Cost Data for Concrete Arch Construction*

Job No.	Item	Quantity	Percent Total Cost**	Partial Percentages, Form + Concr	Number of Structures
1	Forms	38,000 sq ft	38	44	6
	Reinf Steel	36 tons	15		
	Concr	1,080 cu yd	47	56	
2	Forms	2,800 sq ft	40	52	2
	Reinf Steel	7 tons	17		
	Concr	221 cu yd	43	48	
3	Forms	117,090 sq ft	60	68	18
	Reinf Steel***	108 tons	12		
	Concr	2,043 cu yd	28	32	

* - All data for conventionally placed concrete structures.
** - Total cost from sum of items listed.
*** - Estimated data. Contract data not available.

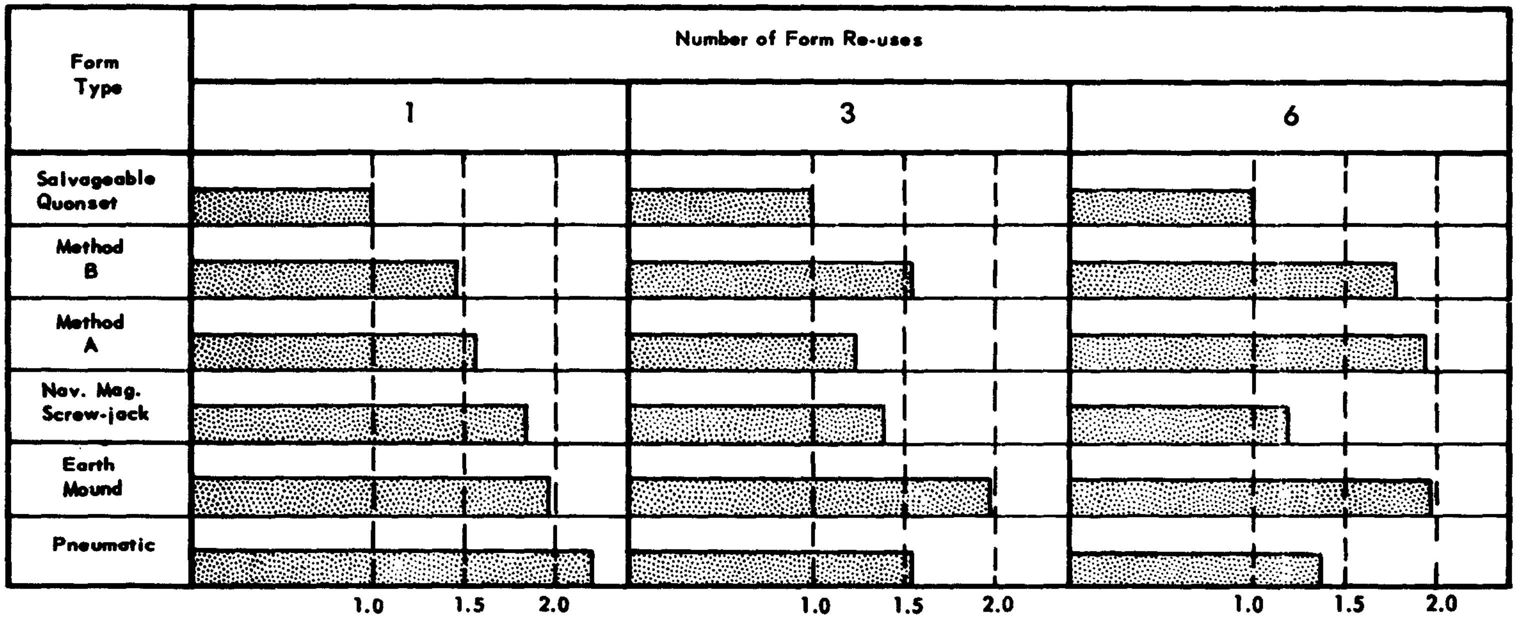


Figure 10. Relative form costs.

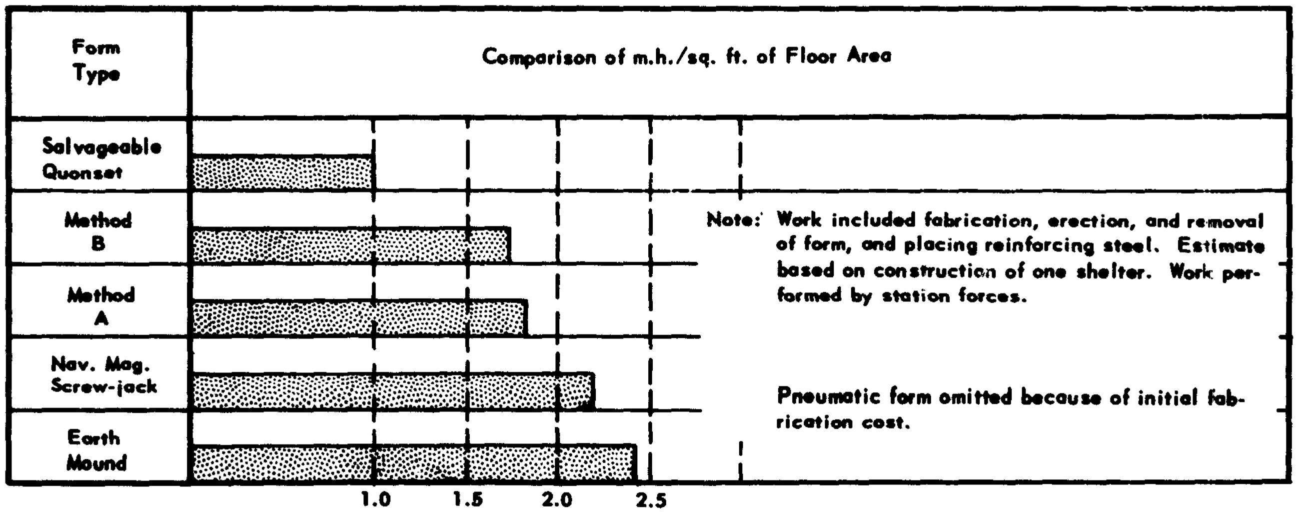


Figure 11. Relative man-hour requirements.

DISCUSSION

Shotcrete

The production rate of shotcrete equipment is presently limited to 8 to 12 cubic yards per hour. When considering the construction of thick-walled arches, which may be built easily by conventional methods of placing concrete, the development of a coarse aggregate shotcrete has been of limited value. For the construction of relatively thin arches, or those of small radii, the development of a controlled pneumatically placed concrete is of considerable importance, in that: (1) a well-designed concrete mix may be used in place of an uneconomical cement mortar mix; (2) air pockets (voids) which are common in pneumatic mortar construction are eliminated; and (3) a single inside face form may be used in place of more expensive double forms.

The pressures which are developed on formwork as a result of shotcrete placement are functions of temperature, hydraulic characteristics of the mix, and the placement rate. The production capability of the Laboratory's shotcrete equipment was only 50 percent of the capability of the equipment presently in use by commercial shotcrete contractors. Thus the factors which influence flexible form deflections were not evaluated. It is believed, however, that balancing the height of lifts on both sides of the structure and perhaps placing shotcrete on the crown section when required will eliminate undesirable form deflections resulting from high placement rates. This is the procedure used in backfilling large flexible conduits.

Forms

All flexible forming methods investigated were satisfactory for the construction of shotcrete arches. The corrugated sheets on one of the Quonset form sections, Figure 3, were badly oxidized. Additional ribs were therefore placed between the existing Quonset ribs to strengthen the form. Additional ribs are not required when the salvageable form materials are in fairly good condition.

Forming Method A was not as rigid as that of Method B; however, no cracking of the shotcrete arches resulted from deflections of either form. The maximum material thickness allowed in fabrication of the flexible plywood forms was 3/8 inch, as the initial stresses developed in curving sheets of greater thickness cracked the outer tension ply. The pipe struts shown in Figure 14 of Appendix B were not necessary; they were designed to provide a factor of safety in event of a form failure by lateral buckling.

The earth mound and the pneumatic form inherently are subject to greater limitations of application than the Quonset or plywood forms but both are structurally acceptable methods. Because of the safe embankment slope for the more common earth-fill materials, a segmental mound (central angle less than 180 degrees) would not provide a practical form for the construction of a shelter with only 1200 square feet of floor area. The exception to this restriction on segmental mounds would occur in the construction of barrel shell roof structures in which the side walls allow use of small ratios of rise to span for the roof, thereby minimizing the slope of the compacted mound.

CONCLUSIONS

1. The use of shotcrete in the construction of semicircular concrete arches results in savings in forming.

2. The cost for placing shotcrete on semicircular forms is no greater than the cost for placing conventional concrete in semicircular forms. Therefore, shotcrete should be considered for the construction of arch-shaped structures.

3. The salvageable Quonset is the most economical form of those evaluated.

4. The flexible plywood forming Method B is more satisfactory than Method A for the construction of a single shelter in which reinforcing steel (0.5 percent or greater) is to be placed in both the inner and outer face of the shotcrete shell.

5. Because of the safe embankment slope for the sandy clay soil the earth mound could not have been constructed without the use of plywood forms.

RECOMMENDATIONS

It is recommended that future work on shotcrete shelter construction consider the following:

1. Properties and characteristics of shotcrete mixes such as density, freezing, and thawing.

2. The efficiency with which freshly placed shotcrete bonds to shotcrete which has taken initial set.

3. The characteristics of water-stop materials with relation to dynamic loading of shelters.

4. The effect of shotcrete placement rate on flexible form deflection.

REFERENCES

1. Breckenridge, R. A., et al. "Blast Loading and Response of Underground Concrete-Arch Protective Structures." Project 3.1, Operation PLUMBBOB, WT-1420, 5 June 1959. U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, and U. S. Naval Civil Engineering Laboratory, Port Hueneme, California (CONFIDENTIAL).

2. American Concrete Institute. "ACI Standard Recommended Practice for the Application of Mortar by Pneumatic Pressure." (ACI 805-51) ACI Journal, Proc. Vol. 47, (May 1959).

3. Holmes and Narver. "Post-Shot Analysis for Project 3.1, Operation PLUMBBOB," for Contract DA-22-079-Eng-196, Modification No. 3. Holmes and Narver, Los Angeles, April 1958 (CONFIDENTIAL).

4. Merritt, J. L., and N. M. Newmark. Design of Underground Structures to Resist Nuclear Blast, Vol. II. University of Illinois, Urbana, Illinois, April 1955.

5. U. S. Army Corps of Engineers. "Design of Structures to Resist the Effect of Atomic Weapons." Design of Buried and Semiburied Structures (Draft), Manual EM-1110-345-421, January 1957.

6. U. S. Naval Civil Engineering Laboratory. Technical Note 167, Investigation of an Airform Ammunition Magazine, by C. K. Wiehle. Port Hueneme, California, 28 August 1953.

7. American Concrete Institute. "Building Code Requirements for Reinforced Concrete." (ACI 318-51) ACI Journal, Proc. Vol. 2.7, (December 1955).

Appendix A

WET-MIX SHOTCRETE

WET-MIX DESIGN

The following guides can be applied in the design of a wet-mix shotcrete:

1. Shotcrete materials should conform to the applicable provisions of the ACI Building Code Requirements for Reinforced Concrete.[7]

2. Fine aggregate gradation should conform as nearly as practical with the ACI ideal gradation curve (Figure 12).

3. Poor quality shotcrete generally results from either a too wet (high-slump) mix or a too rich mix.

4. Advantages obtained by use of concrete admixtures in ready-mix concrete also may be obtained in wet-mix shotcrete.

5. The maximum size of coarse aggregate, generally used in commercial shotcrete mixes, does not exceed 5/8 inch.

6. In shotcrete mixes containing 1/2-inch minus coarse aggregate the coarse aggregate generally will not exceed 33 percent, by absolute volume, of the total aggregate content of the mix.

7. The desired slump for a shotcrete mix containing 3/8-inch pea gravel or 1/2-inch maximum size aggregate is generally between 1 and 1-1/2 inches.

8. Entrained air contents up to 4-1/2 percent by absolute volume are common in commercial shotcrete.

9. An inert filler material such as gray-colored asbestos fibres (shorts) may be beneficial in providing a more plastic mix. White asbestos or long-fibered asbestos should not be used unless verified by experimentation.

10. Type I or Type III portland cement generally is used in wet-mix shotcrete. (ACI specifies Type II in dry mixes.[2])

Table I lists the properties of the shotcrete mixes used at the Laboratory. These mixes exhibited exceptionally good hydraulic characteristics. In designing the mixes, all aggregates which passed a number 4

sieve were considered as fine aggregates. On this basis, a combined coarse and fine aggregate sieve analysis was plotted and the fine aggregate contents of the mixes were adjusted to conform to the ideal sieve analysis of Figure 12.

SHOTCRETE PLACEMENT

Extreme heat, particularly when accompanied by hot winds, causes freshly placed shotcrete to quickly dry out and crack. When such conditions are encountered, the freshly placed concrete should be covered immediately with burlap and kept moist until an additional coating is applied. In wetting the shotcrete surface with water, precaution must be taken to insure that the water will not wash the mortar from the concrete surface.

The rebound characteristics of shotcrete generally prohibit the use of conventional double forms. If double-formed concrete shapes are required, the shotcrete is placed by removing the nozzle from the discharge end of the material hose and reducing the air pressure in the mixing chambers to the minimum pressure that will convey the materials through the hose.

SHOTCRETE PRODUCTION RATE

The production rate of shotcrete equipment varies with the size of the mixing equipment, the air supply, the hydraulic characteristics of the mix, and the time required to reload the mixing chambers.

Available equipment is dependable, easily maintained, and enables placing of shotcrete at rates of from 3 to 12 cubic yards per hour. The small model shotcrete machine used at the Laboratory was rated by the manufacturer at 3 cubic yards per hour when placing a mortar mix consisting of one part cement to four parts sand. The use of a well-designed 3/8-inch pea gravel concrete mix (Table II) permitted doubling the shotcrete placement rate (6.3 cubic yards per hour — based on in-place measurements) and produced a higher strength concrete for the same quantity of cement by enabling reduction of the water-cement ratio.

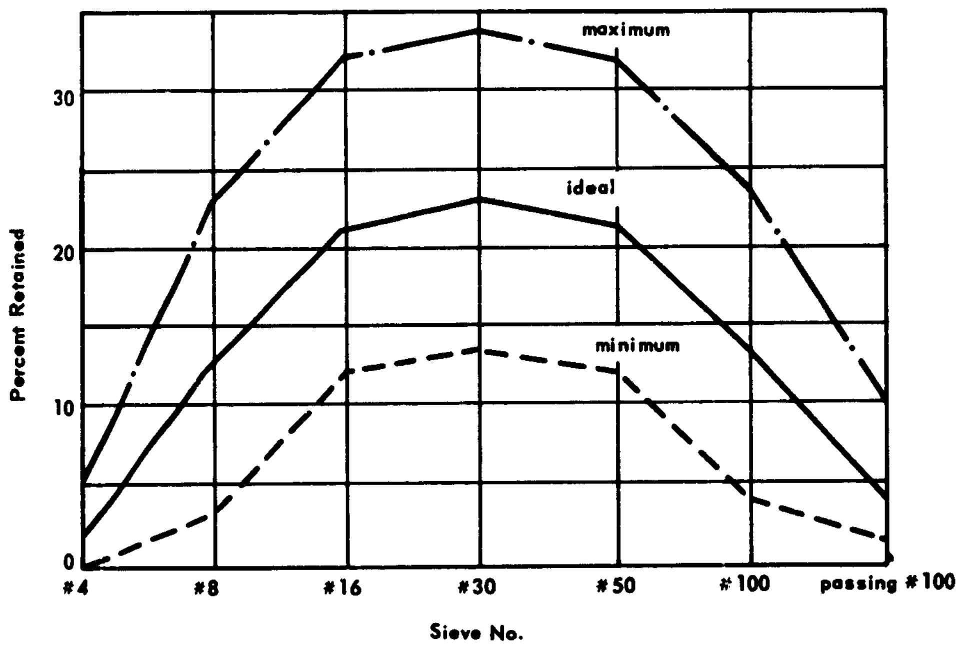


Figure 12. Gradation for shotcrete.

Table II. Shotcrete Mixes

Materials: Southern California Aggregates; Type III High Early Portland Cement

Mix Factor	Mix No. 1	Mix No. 2
Design Strength (7-day), (psi)	5,000	4,000
Test Cylinder Strength (7-day), (psi)	5,850	4,170
Cement Factor (sacks/cu yd)	7.3	7.15
Water-Cement Ratio	0.357 = 4.02/gal/sk	0.352 = 3.97/gal/sk
Fine Aggregate:		
Fineness Modulus	2.67	2.67
Specific Gravity (SSD)	2.58	2.58
Weight/cu yd of concrete (lb)	1,570	1,538
Coarse Aggregate:		
Maximum size	1/2-in. minus	3/8-in. pea gravel
Specific Gravity (SSD)	2.53	2.53
Weight/cu yd of concrete (lb)	1,518	1,485
Admixtures:		
Water Reducing Agent (lb/sk cement)	0.25	0.25
Entrained Air, by volume (%)	0	3

Appendix B

DETAILS OF FORM WORK

QUONSET FORM - REMOVAL AND FOUNDATION DETAILS

In removing the Quonset form from the concrete arch it is necessary to spring the base of the form inward and drop the form vertically. Springing of the form inward is accomplished by use of a pull-jack. The Quonset form may be removed by a minimum vertical drop of 2 inches. However, the standard Quonset floor sill and stringer detail, Figure 13, provides a 6-1/2-inch drop, which expedites removal of the form.

The Quonset form is rugged, consequently traction power equipment (jeep, fork lift, etc.) may be used in pulling the form from the arch. At the Laboratory, four men manually removed a 12-foot form section in approximately 5 minutes. Excavation restrictions in removal of forms from a buried shell will require that the standard Quonset length be sectionalized for form use. If excavation limits are not restrictive, it is believed that little difficulty will be encountered in transporting the Quonset as a composite form.

For the construction of arches of extreme length, the Quonset form may be modified by the addition of rollers or of wheels and track to serve as a traveling form.

FLEXIBLE PLYWOOD FORMS - STRUCTURAL DETAILS AND ERECTION PROCEDURE

Structural details of form Methods A and B are shown in Figures 14 and 15. The erection procedure for Method A is as follows:

1. Lay four of the prefabricated 4-foot by 8-foot plywood sheets end to end on the ground and bolt the 2-inch by 4-inch splice-joint wales to form a 4-foot by 32-foot continuous sheet.

2. Attach the prestressing cables as shown in Figure 15. Leave the center turnbuckles uncoupled.

3. Tilt the continuous form sheet on one 32-foot edge so that it is standing vertically 4 feet high.

4. Place one man at each end and one man at the center of the sheet.

5. Walk the ends of the sheet together to form the approximate curved shape of the finished form.

6. Hold the form in this curved shape and fasten the prestressing cables together at the turnbuckles.

7. Take up the slack in the prestressing cables with the turnbuckles so that the form will remain in its curved shape.

8. Stand the curved form in its normal position and manually place it in position on the shell foundation.

9. Tighten the prestressing cables to pull the form to its designed dimensions.

10. Bolt the form base wale to the foundation.

11. Scab adjacent sections as required.

SUGGESTED MODIFICATIONS TO FLEXIBLE FORMS

If high shotcrete placement rates cause excessive form deflections it is recommended that modifications of the forms and placing be made as follows:

1. Quonset: Add additional ribs to provide a 2-foot rib spacing.

2. Method A: Provide form wales and ties in accordance with the design for the Method B formwork.

3. Method B: Add additional web-trussed reinforcing steel ribs or provide pretensioning cables in accordance with those used in Method A.

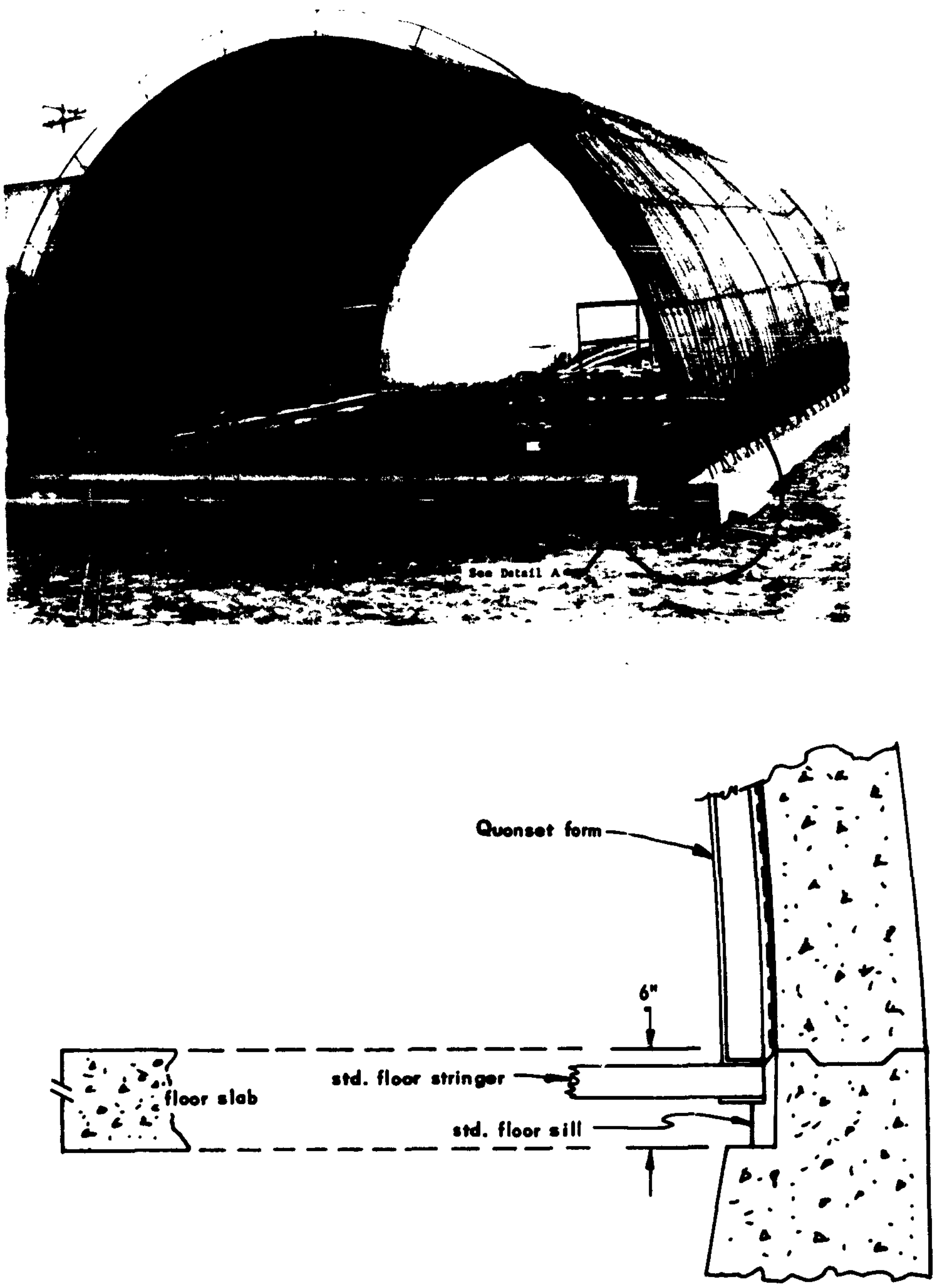
EARTH MOUND FORM - FILL MATERIALS AND FORMWORK

Materials

The fill materials for an earth mound form should contain the minimum percentage of cohesive binder which will allow shaping of the mound surface. If the materials conform to this requirement the excavation capabilities of construction equipment will be increased. During a trial run a trenching machine, operating in reverse and in a well-consolidated sandy material, excavated the material at a rate of 25 cubic yards per hour . This was considerably greater than the 11 cubic yards per hour attained by the same machine during excavation of the mound constructed by the Laboratory.

Formwork

The plywood formwork shown in Figure 5 was used in the construction of the mound as a field expedient. Use of the form shown in Figure 16 is recommended, as the dimensions of the mound may be attained during initial compaction of the fill.



Detail A

Figure 13. Footing detail for Quonset form.

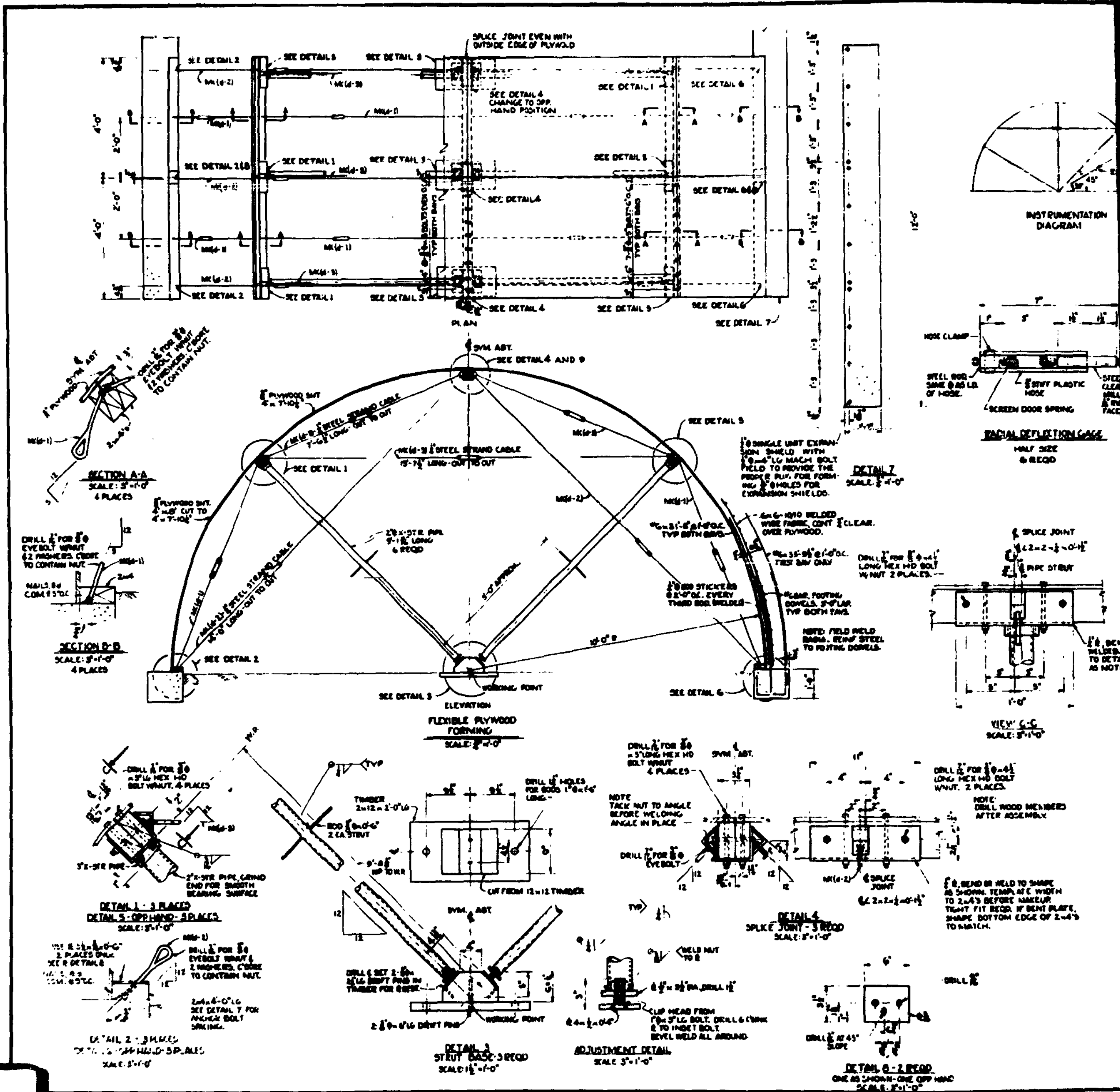


Figure 14. Flexible plywood form — "Method A."

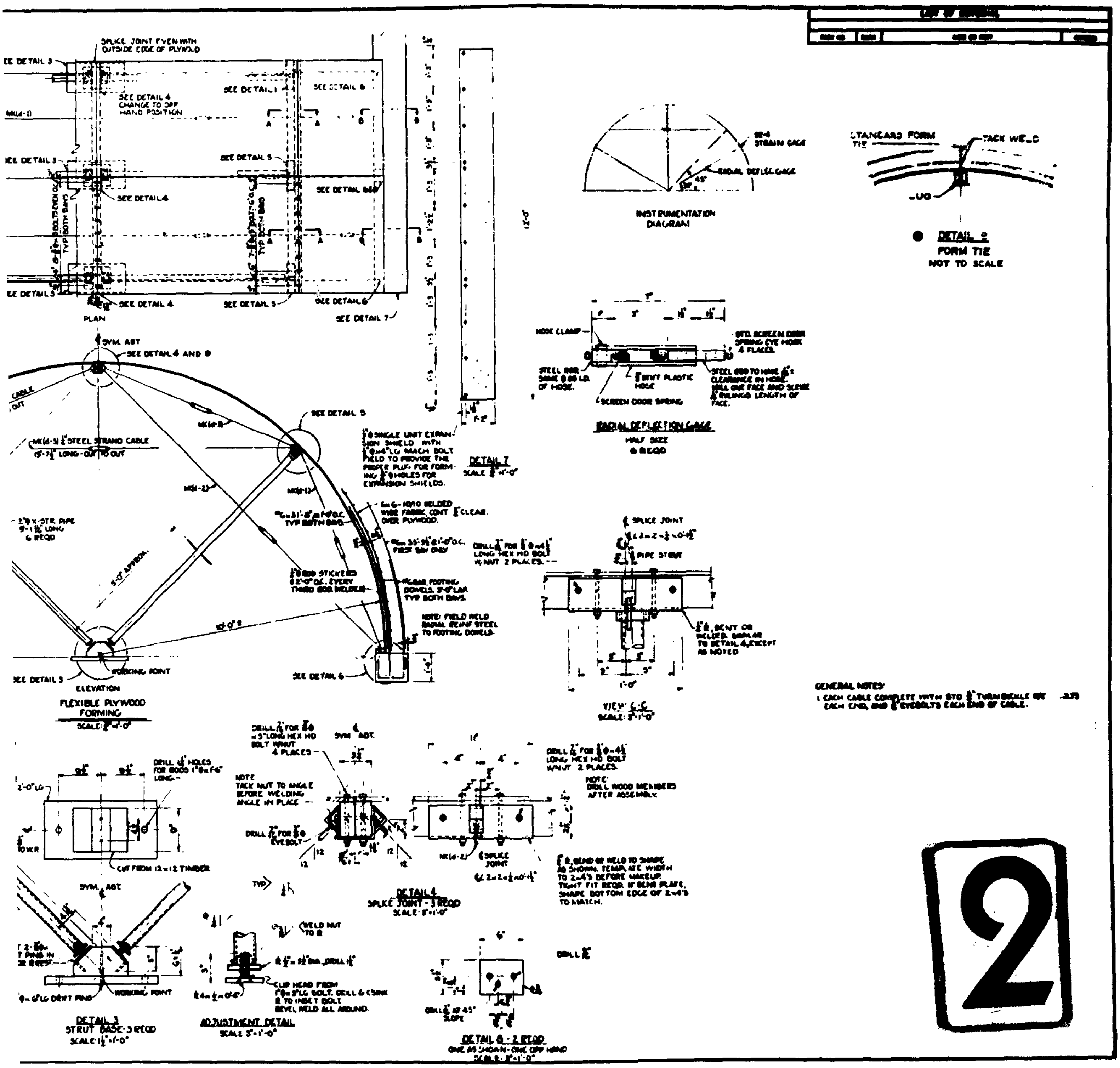


Figure 14. Flexible plywood form — "Method A."

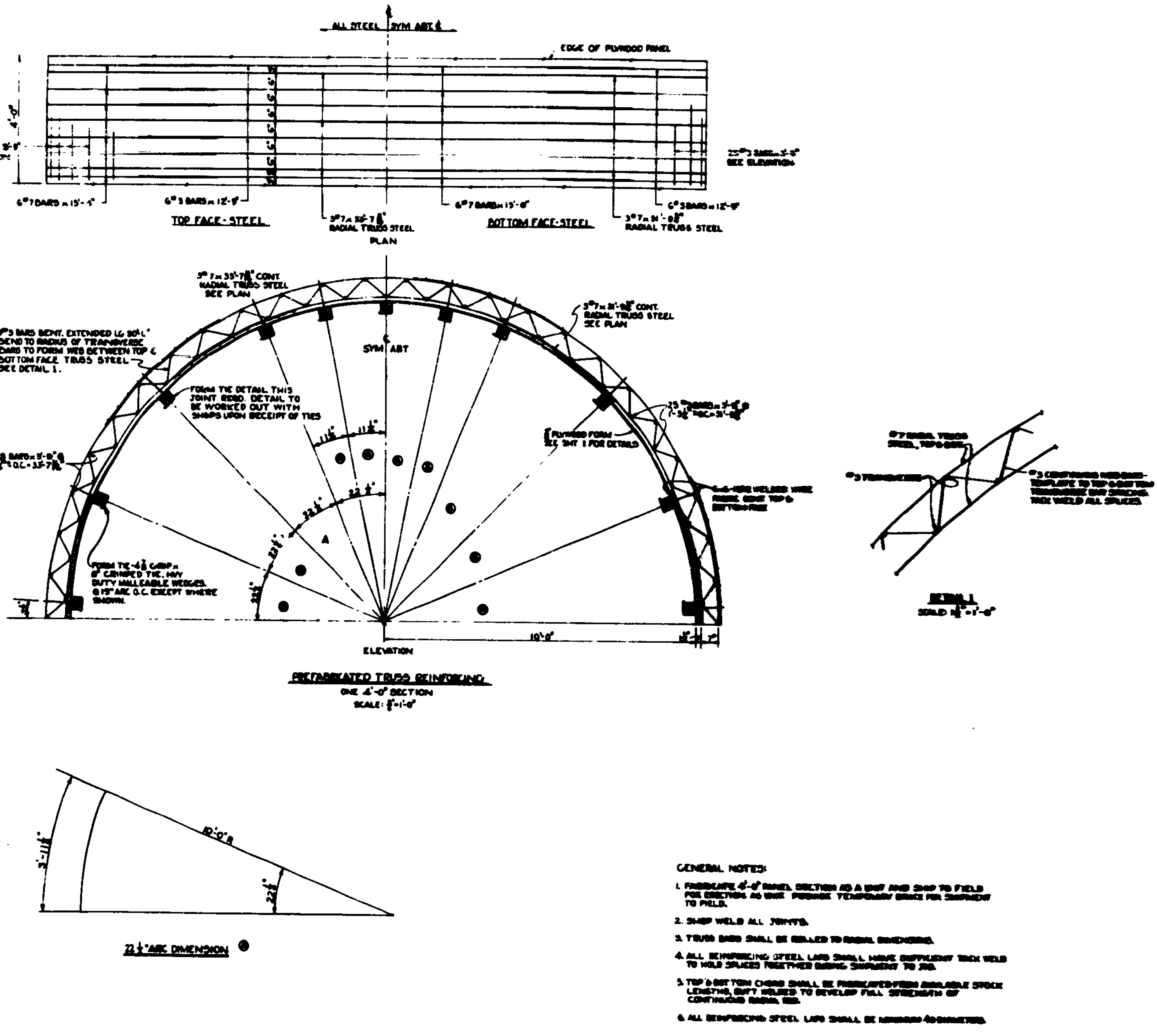


Figure 15. Flexible plywood form — "Method B."

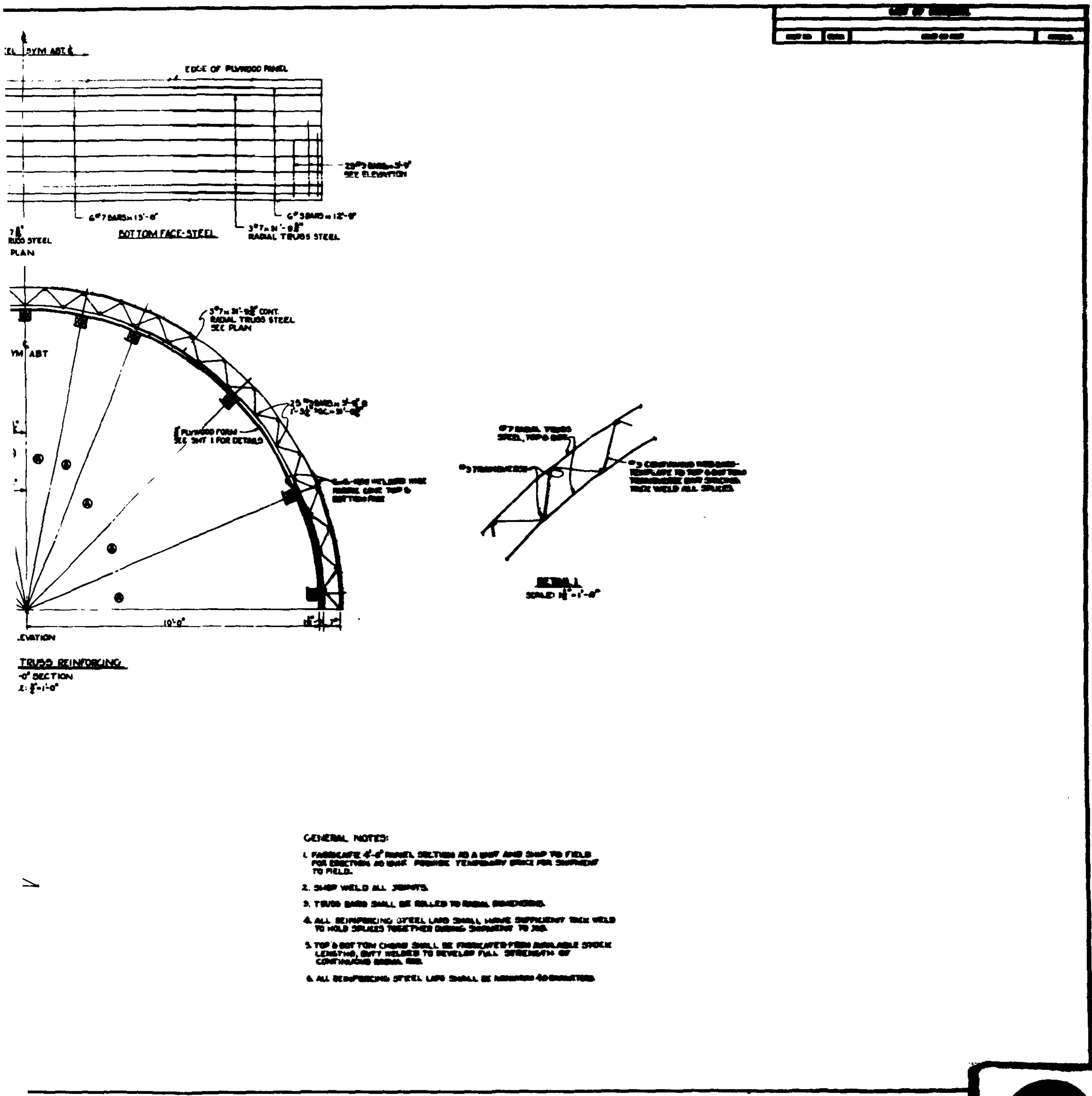


Figure 15. Flexible plywood form — "Method B."

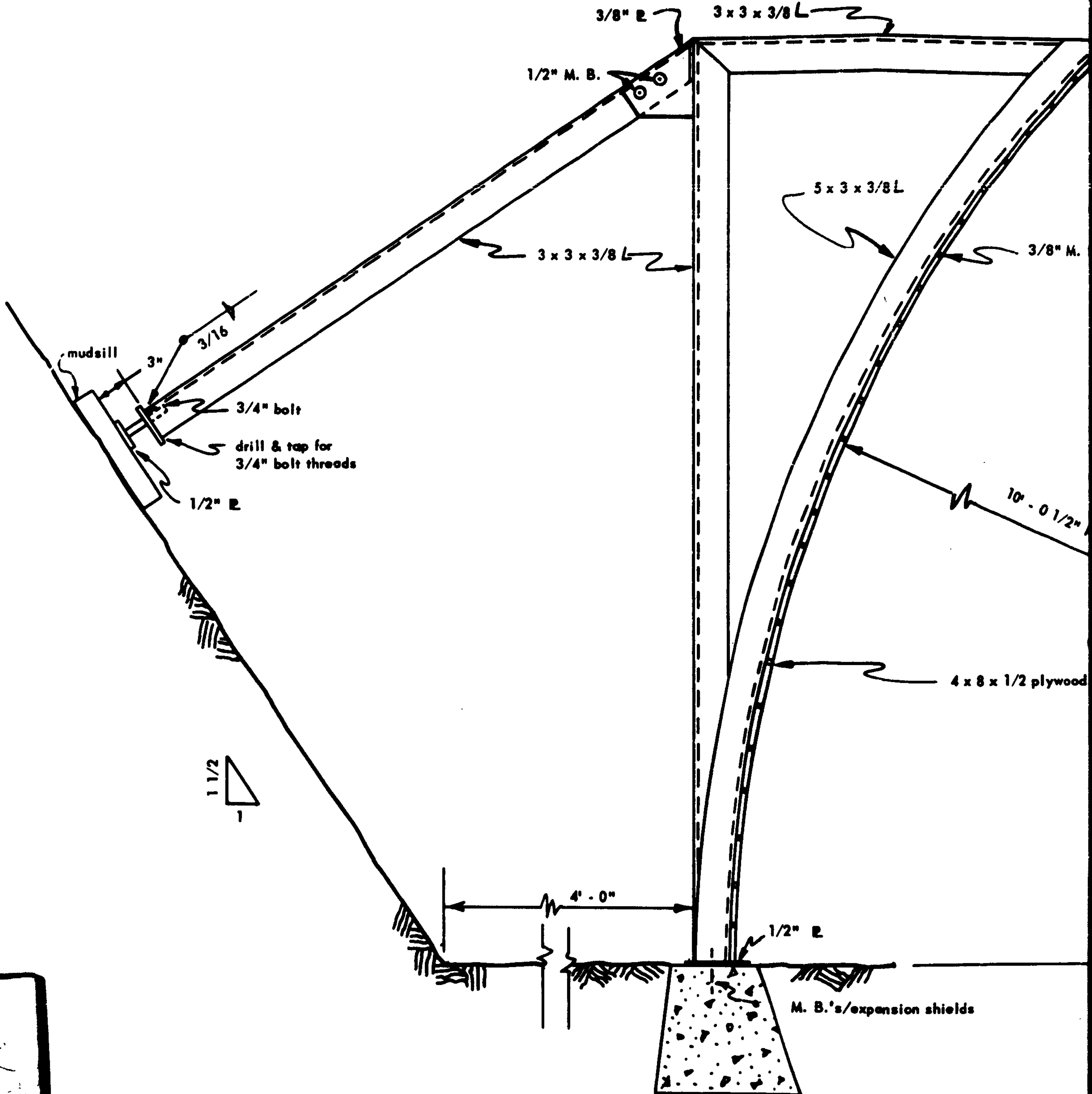


Figure 16. Recommended form for earth mound construction.

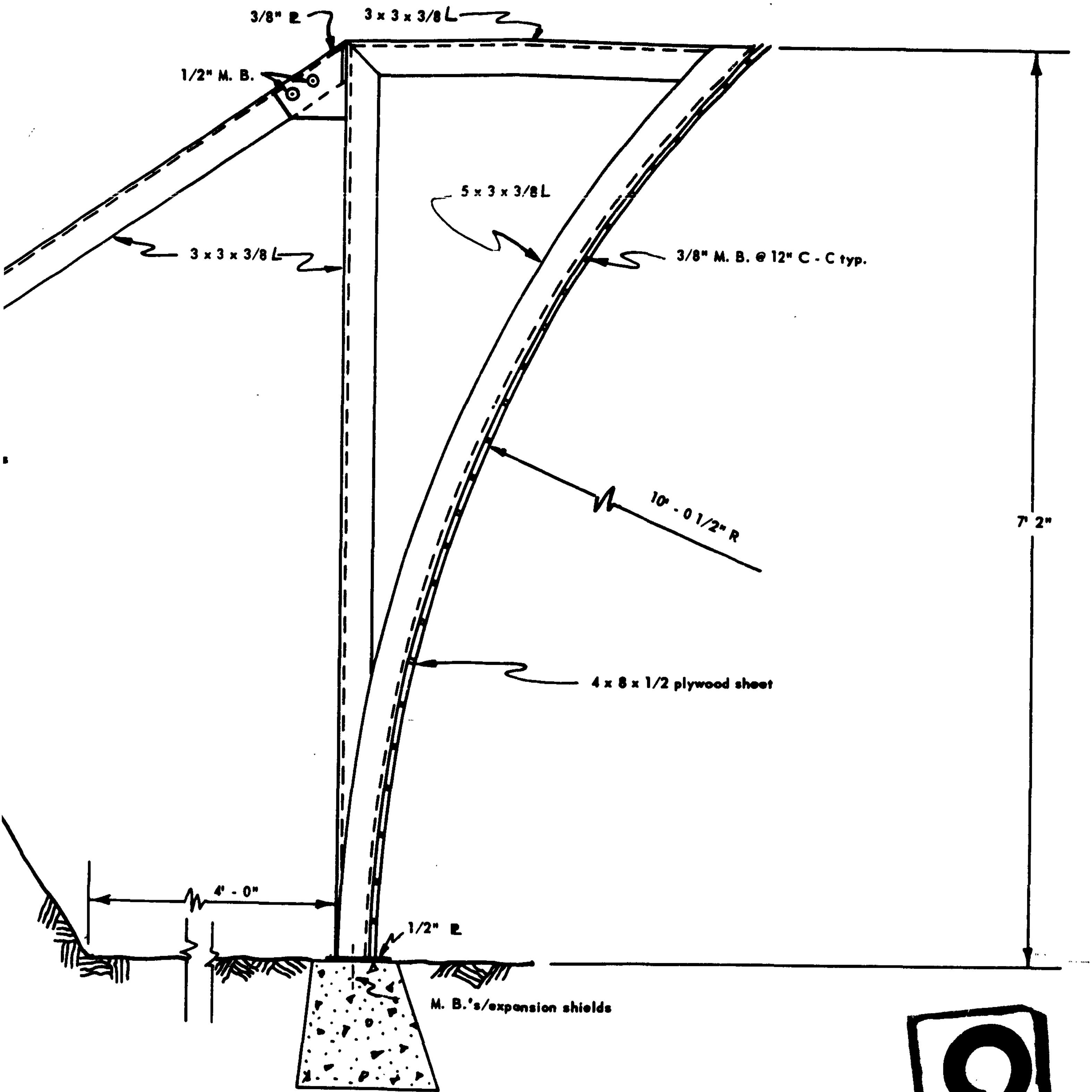


Figure 16. Recommended form for earth mound construction.

2

Appendix C

SHOTCRETE EQUIPMENT

A schematic diagram of a shotcrete machine is shown in Figure 17. Accessory equipment is listed in Table III. Scaffolding for the nozzle crew consisted of a 4-foot by 8-foot steel platform mounted on a fork-lift truck (Figure 1).

Table III. Accessory Shotcrete Equipment

Item	Wet Mix	Dry Mix
Sand Dryer	None	Dry sand (Moisture 3 to 8% normal)
Air Compressor	125-315 cfm Rotary	Required
Mixer	Built in	Required (May be hand-mixed for small production)
Water Pump	City water pressure	Generally required (Water pressure must be 15 psi greater than operating air pressure)
Water Meter	Built in	None
Batch Scales	Required for quality-controlled concrete	None (w/c ratio controlled by material nozzle operator)

Preceding Page Blank

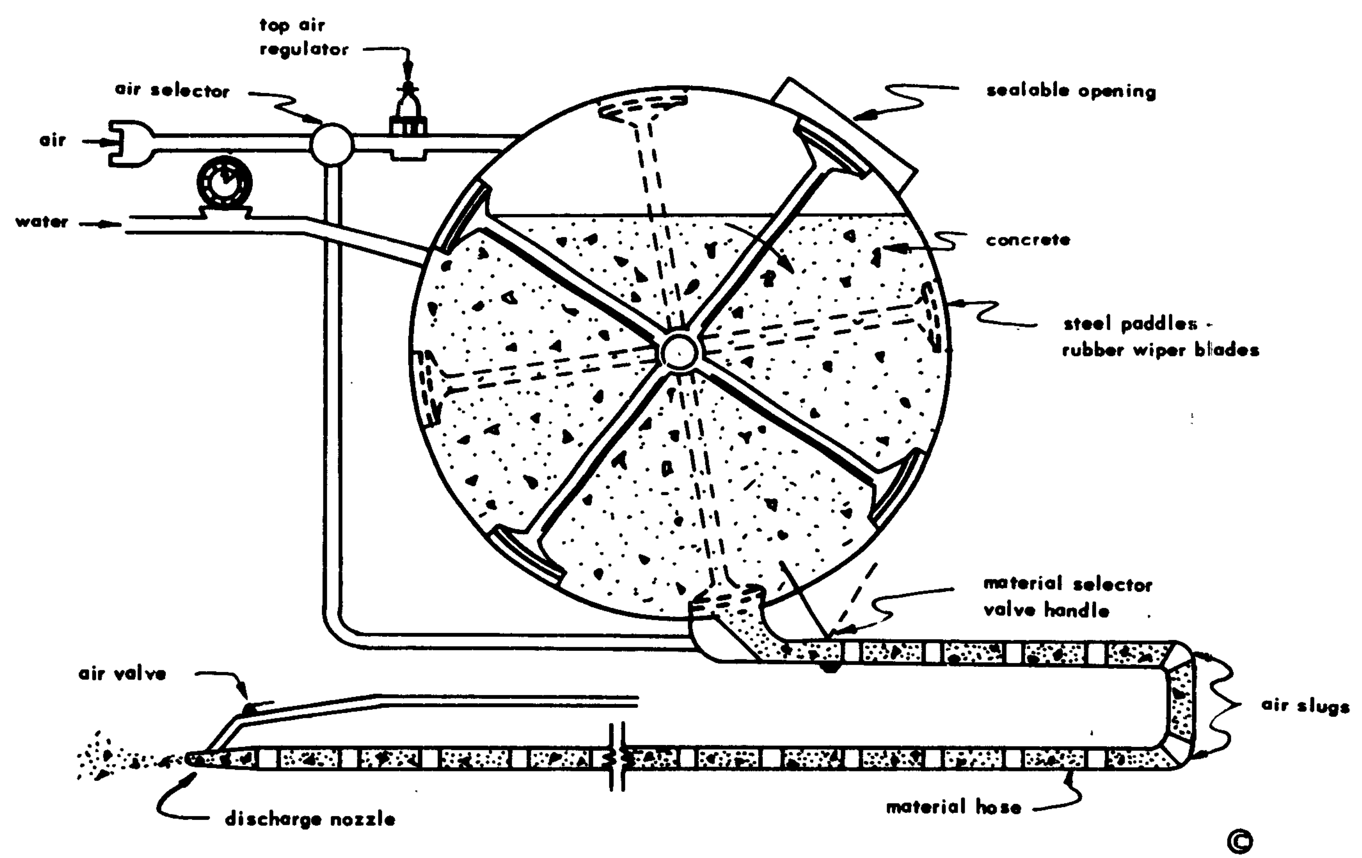


Figure 17. Wet-mix shotcrete machine.

Appendix D

SHOTCRETE PLACING CREW

Number Required	Position	Function
1	Nozzleman	Guides the nozzle
1	Assistant nozzleman	Handles the material hose
1	Air-jet man	Blows rebound off forms
1	Machine operator	Operates shotcrete machine
1	Material loading operator	Operates loading machine
3	General laborers	Shovel aggregate
2	Fork-lift operators	Transport materials

DISTRIBUTION LIST

No. of Copies	SNDL Code	
10		Chief, Bureau of Yards and Docks
		BuDocks Standard Distribution
1	23A	Naval Forces Commanders (Taiwan Only)
2	39B	Construction Battalions
9	39D	Mobile Construction Battalions
3	39E	Amphibious Construction Battalions
2	39F	Construction Battalion Base Units
1	A2A	Chief of Naval Research - Only
2	A3	Chief of Naval Operations (Op-07, Op-04)
5	A5	Bureaus
3	B3	Colleges
2	F4	Laboratory ONR (Washington, D. C. Only)
8	F9	Station - CNO (Boston; Key West; New Orleans; San Juan; Long Beach; San Diego; Treasure Island; and Rodman, C. Z. Only)
5	F17	Communication Station (San Juan; San Francisco; Pearl Harbor; Adak, Alaska; and Guam only)
1	F21	Administration Command and Unit CNO (Saipan only)
2	F40	Communication Facility (Pt. Lyautey and Japan only)
2	F42	Radio Station (Oso and Cheltanham only)
1	F48	Security Group Activities (Winter Harbor only)
8	H3	Hospital (Chelsea; St. Albans; Portsmouth, Va; Beaufort; Great Lakes; San Diego; Oakland; and Camp Pendleton only)
1	H6	Medical Center
2	J1	Administration Command and Unit-BuPers (Great Lakes and San Diego only)
1	J3	U. S. Fleet Anti-Air Warfare Training Center (Virginia Beach only)
2	J4	Amphibious Bases
1	J34	Station - BuPers (Washington, D. C. only)
1	J37	Training Center (Bainbridge only)
1	J48	Construction Training Unit
1	J60	School Academy
1	J65	School CEC Officers
1	J84	School Postgraduate
1	J95	School War College

Distribution List (Cont'd)

No. of copies	SNDL Code	
11	L1	Shipyards
4	L7	Laboratory - BuShips (New London; Panama City; Carderock; and Annapolis only)
5	L26	Naval Facilities - BuShips (Antigua; Turks Island; Barbados; San Salvador; and Eleuthera only)
1	L30	Submarine Base (Groton, Conn. only)
2	L32	Naval Support Activities (London & Naples only)
2	L42	Fleet Activities - BuShips
7	M28	Supply Depot (Except Guantanamo Bay; Subic Bay; and Yokosuka)
2	M61	Aviation Supply Office
3	N1	BuDocks Director, Overseas Division
42	N2	Public Works Offices
7	N5	Construction Battalion Center
5	N6	Construction Officer-in-Charge
1	N7	Construction Resident-Officer-in-Charge
12	N9	Public Works Center
1	N14	Housing Activity
1	R20	Marine Corps Schools, Quantico
3	R64	Marine Corps Base
1	R66	Marine Corps Camp Detachment (Tengan only)
7	W1A1	Air Station
35	W1A2	Air Station
9	W1B	Air Station Auxiliary
5	W1C	Air Facility (Phoenix; Monterey; Oppama; Naha; and Naples only)
3	W1E	Marine Corps Air Station (Except Quantico)
1	W1F	Marine Corps Auxiliary Air Station
8	W1H	Station - BuWeps (Except Rota)

No. of copies	
1	Chief of Staff, U. S. Army, Chief of Research and Development, Department of the Army, Washington 25, D. C.
1	Office of the Chief of Engineers, Asst. Chief of Engineering for Civil Works, Department of the Army, Washington 25, D. C.
1	Chief of Engineers, Department of the Army, Attn: Engineering R & D Division, Washington 25, D. C.
1	Commanding Officer, Engineering R & D Laboratories, Attn: Technical Intelligence Branch, Fort Belvoir, Virginia
1	Commanding General, Wright Air Development Center, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio
1	Deputy Chief of Staff, Development, Director of Research and Development, Department of the Air Force, Washington

Distribution List (Cont'd)

No. of copies	
1	President, Marine Corps Equipment Board, Marine Corps Schools, Quantico, Virginia
1	Director, National Bureau of Standards, Department of Commerce, Connecticut Avenue, Washington, D. C.
10	Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia
1	Deputy Chief of Staff, Research and Development Headquarters, U. S. Marine Corps
3	Headquarters, USAF, Directorate of Civil Engineering, Attn: AFOCE-ES, Washington 25, D. C.
2	Commander, Headquarters, Air Research and Development Command, Andrews Air Force Base, Washington 25, D. C.
2	Office of the Director, U. S. Coast and Geodetic Survey, Washington 25, D. C.
2	Library of Congress, Washington 25, D. C.
10	Director, Office of Technical Services, Department of Commerce, Washington 25, D. C.
	NCEL Standard Distribution
2	Director of Defense Research and Engineering, Department of Defense, Washington 25, D. C.
2	Director, Division of Plans and Policies, Headquarters, U. S. Marine Corps, Washington 25, D. C.
2	Director, Bureau of Reclamation, Washington 25, D. C.
2	Commanding Officer, U. S. Naval Construction Battalion Center, Attn: Technical Division, Code 141, Port Hueneme, California
2	Commanding Officer, U. S. Naval Construction Battalion Center, Attn: Materiel Department, Code 142, Port Hueneme, California
1	Commanding Officer (Patent Dept.), Office of Naval Research Branch Office, 1030 E. Green Street, Pasadena, California
	NCEL Supplemental Distribution
1	Mr. E. E. Shalowitz, Protective Construction, GSA Building, 19th and F Streets, N. W., Washington, D. C.
1	Mr. G. H. Albrigth, The Pennsylvania State University, College of Engineering and Architecture, University Park, Penn.
1	Lt. Col. Russell J. Hutchinson, 052921, Office of Area Engineer, Saudi Arabia, U. S. A. Engineer District, Trans-East, APO 616, New York
1	Capt. A. B. Chilton, Jr., CEC, USN, U. S. Naval Civil Engineering Laboratory, Port Hueneme, Calif.
1	Cdr. C. A. Grubb, CEC, USN, District Public Works Office, 11th Naval District, 1220 Pacific Highway, San Diego
1	Capt. W. M. McLellon, CEC, USN, Public Works Officer, U. S. Naval Base, Charleston, S. C.
1	Capt. L. N. Saunders, Jr., CEC, USN, Bureau of Yards and Docks (D-400), Department of the Navy, Washington, D. C.
1	Cdr. J. F. Clarke, CEC, USN, Area Public Works Office, Chesapeake, U. S. Naval Weapons Plant, Washington, D. C.
1	Lcdr. W. J. Francy, CEC, USN, Bureau of Yards and Docks (Code D-500), Department of the Navy Washington, D. C.

No. of copies	
1	Lcdr. H. A. Locke, CEC, USN, Camp Smedley D. Butler, U. S. Marine Corps, Navy No. 161, FPO, San Francisco
1	Lcdr. W. H. Sturman, CEC, USN, San Francisco Naval Shipyard, San Francisco
1	Mr. A. F. Dill, The Pennsylvania State University, College of Engineering and Architecture, University Park, Penn.
1	Capt. J. H. Barker, Jr., CEC, USN, U. S. Naval Missile Center, Point Mugu, Calif.
1	Cdr. W. J. Christensen, CEC, USN, Bureau of Yards and Docks, Code D-440, Department of the Navy, Washington, D. C.
1	Capt. J. H. Lofland, Jr., CEC, USN, Pearl Harbor Naval Shipyard, Navy No. 128, FPO, San Francisco
1	Capt. W. A. McManus, CEC, USN, U. S. Naval Air Station, Norfolk, Va.
1	Lcdr. J. D. Andrews, CEC, USN, Defense Atomic Support Agency, Washington, D. C.
1	Cdr. D. P. Cunning, CEC, USN, District Public Works Office, 4th Naval District, Naval Base, Philadelphia, Penn.
1	Lcdr. C. Curione, CEC, USN, District Public Works Office, 14th Naval District, Navy No. 128, FPO, San Francisco
1	Cdr. H. L. Murphy, CEC, USNR, Field Command, Defense Atomic Support Agency, Sandia Base, Albuquerque, N. M.
1	Lcdr. W. A. Walls, CEC, USN, Defense Atomic Support Agency, Washington, D. C.
1	Cdr. C. F. Krickenberger, CEC, USN, U. S. Naval Amphibious Construction Battalion Two, FPO, New York
1	Cdr. H. W. Stephens, CEC, USN, District Public Works Office, 12th Naval District, San Bruno, Calif.
1	Lcdr. C. R. Whipple, CEC, USN, Graduate School, University of Illinois, Urbana, Ill.
1	Lcdr. N. W. Clements, CEC, USN, U. S. Navy Nuclear Power Unit, U. S. Army Engineer Center, Fort Belvoir, Va.
1	Mr. Neal FitzSimmons, Office of Civil and Defense Mobilization, 517 Winder Building, Washington, D. C.
1	Lcdr. E. M. Saunders, CEC, USN, NROTC Unit, Stanford University, Palo Alto, Calif.
1	Lcdr. B. S. Merrill, CEC, USN, U. S. Naval Station, Navy No. 138, FPO, New York,
1	Lcdr. R. C. Vance, CEC, USN, U. S. Naval School, CEC Officers, U. S. Naval Construction Battalion Center, Port Hueneme, Calif.
1	Lcdr. J. C. LeDoux, CEC, USN, U. S. Naval School, CEC Officers, U. S. Naval Construction Battalion Center, Port Hueneme, Calif.
1	Lcdr. W. D. Wilson, CEC, USN, Public Works Center, Navy No. 926, FPO, San Francisco
1	Mr. Marshall Wood, National Planning Commission, 1606 New Hampshire Avenue, Washington, D. C.
1	Commandant, Industrial College of the Armed Forces, Washington, D. C.
1	Commandant, U. S. Armed Forces Staff College, U. S. Naval Base, Norfolk, Va.
1	Chief, Bureau of Ships, Attn: Chief of Research and Development Division, Navy Department, Washington, D. C.
1	Commanding Officer, Fleet Training Center, Navy No. 128, % FPO, San Francisco

Distribution List (Cont'd)

No. of copies	
1	Office of Naval Research, Branch Office, Navy No. 100, Box 39, FPO, New York
1	U. S. Army, Attn: Director of Research and Development Group, Washington, D. C.
1	Frost Effects Laboratory, Corps of Engineers, Waltham, Mass.
1	Officer in Charge, U. S. Navy Unit, Rensselaer Polytechnic Institute, Troy, N. Y.
1	Chief, Bureau of Medicine and Surgery, Attn: Research Division, Navy Department, Washington, D. C.
1	Officer in Charge, U. S. Naval Supply Research and Development Facility, Naval Supply Center, Attn: Library, Bayonne, N. J.
1	Chief Bureau of Naval Weapons, Attn: Research Division, Navy Department, Washington, D. C.
1	Commander, Pacific Missile Range, Attn: Technical Director, Point Mugu, California
1	Commander, Amphibious Force, U. S. Atlantic Fleet, U. S. Naval Base, Norfolk, Va.
1	Commander, Amphibious Force, U. S. Pacific Fleet, San Diego
1	Officer in Charge, U. S. Naval Supply Research and Development Facility, Naval Supply Center, Bayonne, N. J.
1	Commanding Officer, Yards and Docks Supply Office, U. S. Naval Construction Battalion Center, Port Hueneme, Calif.
1	Commanding Officer, U. S. Naval Unit, U. S. Army Chemical Corps School Fort McClellan, Ala.
1	U. S. Naval Research Laboratory, Chemistry Division, Washington, D. C.
1	Commanding Officer, Field Research Laboratory, Bureau of Medicine and Surgery, Camp Lejeune, N. C.
1	Commandant, 1st Naval District, Attn: CEC Naval Reserve Program Officer, 495 Summer Street, Boston, Mass.
1	Commandant, 3rd Naval District, Attn: CEC Naval Reserve Program Officer, 90 Church Street, New York
1	Commandant, 4th Naval District, Attn: CEC Naval Reserve Program Officer, Naval Base, Philadelphia, Penn.
1	Commandant, 5th Naval District, Attn: CEC Naval Reserve Program Officer, Norfolk, Va.
1	Commandant, 6th Naval District, Attn: CEC Naval Reserve Program Officer, U. S. Naval Base, Charleston, S. C.
1	Commandant, 8th Naval District, Attn: CEC Naval Reserve Program Officer, U. S. Naval Station, New Orleans, La.
1	Commandant, 9th Naval District, Attn: CEC Naval Reserve Program Officer, Building 1, Great Lakes, Ill.
1	Commandant, 11th Naval District, Attn: CEC Naval Reserve Program Officer, 937 N. Harbor Drive, San Diego
1	Commandant, 12th Naval District, Attn: CEC Naval Reserve Program Officer, Federal Office Building, San Francisco
1	Commandant, 13th Naval District, Attn: CEC Naval Reserve Program Officer, Seattle, Wash.
1	Deputy Chief of Staff, Research & Development Headquarters, U. S. Marine Corps, Washington, D. C.
1	Commander, U. S. Naval Shipyard, Attn: Materials and Chemical Lab., Boston, Mass.
1	Commander, U. S. Naval Shipyard, Attn: Material Laboratory, Brooklyn, N. Y.

Distribution List (Cont'd)

No. of copies	
1	Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U. S. Army, 1215 Washington Avenue, Wilmette, Ill.
1	Chief, Concrete Division, Waterways Experiment Station, P. O. Drawer 2131, Jackson, Miss.
1	Arctic Health Research Center, P. O. Box 960, Anchorage, Alaska
1	Air Force Cambridge Research Center, Hanscom Field, Bedford, Mass.
1	Commander, Air Research & Development Command, Attn: Library, Andrews Air Force Base, Washington, D. C.
1	Directorate of Research, Air Force Special Weapons Center, Kirtland Air Force Base, N. M.
1	Navy Liaison Officer, Detroit Arsenal, Centerline, Mich.
1	Commanding Officer, Signal Corps Engineering Labs, Fort Monmouth, N. J.
1	President, Chemical Warfare Board, Army Chemical Center, Md.
1	Directorate of Medical Research, Chemical Warfare Laboratory, Army Chemical Center, Md.
1	U. S. Army Corps of Engineers, Office of the District Engineer, St. Paul District, 1217 U. S. P. O. and Customs House, St. Paul, Minn.
1	Sandia Corporation, Attn: Classified Document Division, Box 5800, Albuquerque, N. M.
1	Chief, Physical Research Branch, Research Division, U. S. Department of Commerce, Bureau of Public Roads, Washington, D. C.
1	Operation Civil, University of California, Richmond Field Station, Berkeley, Calif.
1	Library, University of Alaska, Fairbanks, Alaska
1	Library, Engineering Department, Stanford University, Stanford, Calif.
1	Library, Harvard University, Graduate School of Engineering, Cambridge, Mass.
1	Director, Engineering Research Institute, University of Michigan, Ann Arbor, Mich.
1	Library, Engineering Department, University of California, 405 Hilgard Avenue, Los Angeles
1	Library, University of Southern California, University Park, Los Angeles
1	Director, Soil Physics Laboratory, Department of Engineering, Princeton University, Princeton, N. J.
1	Director, Soil Physics Laboratory, Department of Engineering, Attn: Library, Princeton University, Princeton, N. J.
1	Director, The Technological Institution, Northwestern University, Evanston, Ill.
1	Library, Institute of Technology, University of Minnesota, Minneapolis, Minn.
1	Library, California Institute of Technology, Pasadena, Calif.
1	Chief, Bureau of Yards and Docks, Code D-230, Washington, D. C.
1	Chief of Engineers, Department of the Army, Washington, D. C.
1	Mr. J. O'Sullivan, The Mitre Corporation, P. O. Box 208, Lexington, Mass.
1	Lcdr. Gordon L. Nelson, Agricultural Engineering Department, Oklahoma State University, Stillwater, Okla.
2	Commander, Pacific Missile Range, U. S. Naval Missile Center, Point Mugu, Calif.
1	Commanding Officer, U. S. Naval Ordnance Laboratory, Corona, Calif.